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TRANSMISSION OF HEAT
THROUGH
COLD-STORAGE INSULATION

PAULDING

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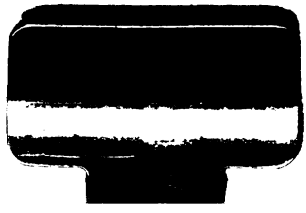

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THE

Transmission of Heat

THROUGH

Cold-Storage Insulation

FORMULAS, PRINCIPLES, AND DATA RELATING TO
INSULATION OF EVERY KIND

A MANUAL FOR REFRIGERATING ENGINEERS

BY

CHARLES P. PAULDING, M.E.

NEW YORK

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PREFACE.

THE laws and experiments given by the French physicist, Péclet, in his famous "Traité de la Chaleur," have been the basis of all treatises on artificial heating that have since been written.

They are equally applicable to the art of refrigeration, and it is the purpose of this book to present them in convenient form with the additional data required for modern practice.

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THE TRANSMISSION OF HEAT THROUGH COLD-STORAGE INSULATION.

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1. **General Principles.**—Let figure 1 represent a section of a wall of a refrigerated room, and let the wall be of the same material throughout its thickness. Let this room be maintained at a constant temperature, lower than that of the external air, by the withdrawal of heat from it by any of the usual methods. Assume the room to be filled, or partially filled, by articles in storage, and suppose that the temperature of the air in the room and that of the air on the outside have remained constant long enough for the flow of heat in through the wall to have become steady; in other words, that the wall has become as cold as under these conditions it ever will become.

Consider, first, the inner surface of the wall; on account of the difficulty which heat experi-

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ences in escaping from the surface of a body, this surface is appreciably warmer than the air within the room, and it gives out heat to the room in two ways, by *radiation* and by *air contact.*

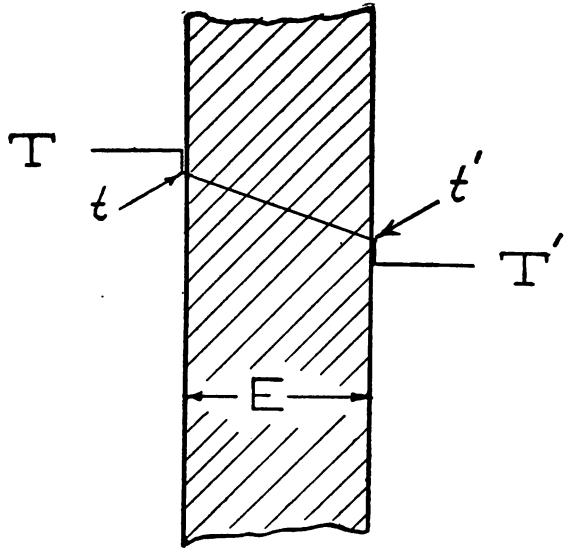

FIGURE 1.

The radiant heat travels in straight lines from the wall-surface to the objects in the room, passing through the air without much, if any, heating of it, but the heat thus imparted to the objects is given up by them to the air by air contact. The objects receiving the radiant heat will evi-

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dently be at a temperature slightly higher than the air; we may neglect this in all calculations, but in measuring the air temperature of a refrigerated room by a thermometer we should always take care to protect it from radiation from the walls, and we should also prevent it from radiating heat to any cooling-surfaces such as brine pipes and so forth.

The heat given out by air contact, or convection, as it is perhaps more usually called, is emitted by the wall-surface to the air actually in contact with that surface. As this air is heated it rises, forming an ascending current along the surface, and therefore the higher the wall the less energetic is this action, although the decrease with height is less than might be expected.

The heat thus given to the air and that absorbed by it by contact with the objects heated by radiation is, of course, carried by it to the cooling-pipes; it enters these and is carried away by the cooling-liquid or gas circulating through them.

Turning to the outer wall-surface we again find a sudden difference of temperature between the air and the surface, this difference being necessary to draw the heat in through the resistance of

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the surface. Part of the heat is radiated to the surface from the surrounding objects and the rest is brought to it by air contact; in this case the current of air along the surface is a descending one instead of an ascending one, as in the case of the inner wall-surface.

Once within the wall, the heat is drawn through the body of it by the difference of temperature between the inner and outer surface. In a homogeneous wall, such as we are considering, the temperature of the wall decreases regularly from the outer to the inner surface, forming a steady slope down which the heat flows by virtue of the conductivity of the insulation. The difference of temperatures governing this action is that of the surfaces, and must not be confused with that of the inner and outer air.

For a given area of wall, the quantities of heat absorbed by the outer surface, transmitted through the body of the wall and emitted by the inner surface, must evidently be equal during any given period of time and constant conditions of temperature.

Having outlined the general principles we now turn to the methods and data for numerical calculations.

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2. Radiation.—"The quantity of heat emitted by radiation per square foot of surface per hour is independent of the form and size of the body, provided that its surface has no reëntrant portions; it depends solely on the nature of the surface, on the excess of its temperature over that of the objects to which radiation takes place, and on the absolute value of the temperature of these objects.*

It makes no difference whether the surface is radiating heat to other objects, as is the case for the inner surface of a wall of a refrigerated room, or is receiving heat by radiation from other objects, as is the case for the outer wall-surface, the amount of heat emitted or absorbed will be the same for otherwise identical circumstances.

For all practical purposes connected with insulation we may simply take the radiation to be proportional to the difference of temperature between the wall and the objects radiated to, although this is not precisely true, and we may entirely neglect the variation due to the particular temperature of the objects radiated to, but as there will always arise special cases in which these

* Péclet. Traité de la Chaleur.

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variations might be important, and also in order that individual judgment may have free play, we will give the necessary tables for more exact calculations.

TABLE I.* VALUES OF K FOR DIFFERENT SURFACES.

In B.T.U. radiated per hour, per square foot, per one degree difference of temperature between temperature of surface and temperature of objects radiated to.

Polished silver	.027	Zinc	.049
Silvered paper	.085	Polished tin	.044
Polished brass	.053	Tin plate	.086
Gilded paper	.047	Sheet iron—polished	.092
Polished copper	.033	Sheet iron—leaded	.133
Cast iron—new	.649	Sheet iron—ordinary	.567
Cast iron—rusted	.688	Sheet iron—rusted	.688
Glass	.596	Building-stone	.737
Powdered chalk	.680	Plaster and brick	.737
Sawdust	.723	Wood	.737
Powdered charcoal	.700	Woolen cloth	.753
Fine sand	.741	Calico or canvas	.747
Oil paint	.759	Silk	.759
Paper	.772	Water	1.087
Lampblack	.820	Oil	1.482

Thus in our calculations any painted wall which is three degrees cooler than the objects radiating heat to it would absorb $3 \times .759 = 2.28$ B.T.U. per hour per square foot. For more refined estimates we modify the figures of Table I by multiplying by a coefficient c' depending on the difference of temperatures, and then by another coefficient c'' varying with the tempera-

* Péclet. Traité de la Chaleur.

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ture of the objects to which radiation takes place. Then the number of B.T.U. radiated per hour per square foot is

$$K \times c' \times c'' \times \text{diff. of temp.} \quad . \quad . \quad (1)$$

The difference of temperature is, as before, that between the radiating surface and the objects radiated to.

TABLE II. VALUES OF c'.

Difference of Temperature between Surface and Objects Radiated to	c'.
5	1.11
10	1.12
20	1.14
40	1.18
80	1.28
160	1.54
320	2.30

TABLE III. VALUE OF c''.

Temperature of Objects Radiated to	c''.
0	.80
20	.86
40	.93
60	1.01
80	1.10
100	1.19
150	1.47
200	1.82

Now return to the example given just after Table I, and assume that the painted wall is at a temperature of thirty-three degrees and the

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objects to which it radiates at a temperature of thirty degrees; then we have by formula (1)

$$\text{Heat radiated} = .759 \times 1.11 \times .90 \times 3 = 2.28.$$

This result is the same that we obtained before. Now it will be shown further on that it is necessary for simplification to use a value of K, the mean between that for the outer wall and that for the inner. An inner temperature of fifteen degrees and outer of forty-five degrees would give the conditions used in the above calculation. Take an inner temperature of forty degrees and an outer of eighty degrees, then the mean is sixty and we would have

$$\text{Heat radiated} = .759 \times 1.11 \times 1.01 \times 3 = 2.55.$$

These cases are toward the two extremes of practice, yet the difference is only about one ninth part of the smaller. If we had been using the two values of K, .759 and $.759 \times 1.11 \times 1.01 = .85$, in computing the loss of heat through a wall six inches thick of any ordinary insulating material the difference in the result would have been about one per cent, which is less than the probable error of any calculation of this kind.

3. Air Contact.—"The loss of heat arising from air contact is independent of the nature of the

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surface of the body, and of the absolute value of the temperature of the surrounding air; it depends solely on the excess of the temperature of the body over that of the surrounding air, and on the form and dimensions of the body."*

In all calculations in this book, unless specifically stated otherwise, we will assume the air-contact loss to vary directly as the difference of temperatures of the air and of the wall-surface and will take the loss for plane vertical walls directly from the following table.

Thus for a wall thirty-two feet high at a temperature of eighty degrees and exposed to air at a temperature of eighty-three degrees the heat absorbed per square foot per hour by air contact will be $=K' \times$ diff. of temp. $= .27 \times 3 = .81$.

TABLE IV. VALUES OF K' FOR A PLANE VERTICAL WALL.

In B.T.U. per hour, per square foot, per one degree difference of temperature of wall-surface and surrounding air.

Height of Wall in Feet.	Value of K'.
1	.40
2	.35
4	.32
8	.30
16	.28
32	.27
64	.26

* Péclet. Traité de la Chaleur.

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As the air-contact loss, like the radiation loss, does not vary precisely as the difference of temperature, we will give the following formulas and tables for those who may wish to make more exact calculations.

The air-contact loss in B.T.U. per square foot per hour

$$= K' \times c \times \text{diff. of temp.}, \quad . \quad . \quad . \quad (2)$$

in which the difference of temperature is that between the surface and the surrounding air, c a coefficient depending on this difference of temperature and to be taken from Table V, and K' a number depending on the form and size of the object and given by the following formulas.

For vertical plane surfaces

$$K' = .361 + \frac{.233}{\sqrt{h}}, \quad . \quad . \quad . \quad . \quad (3)$$

where h is the vertical height of the surface in feet.

For horizontal pipes of circular section

$$K' = .421 + \frac{.307}{r}, \quad . \quad . \quad . \quad . \quad (4)$$

where r equals the outside radius in inches.

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For vertical pipes of circular section

$$K' = .204\left(.726 + \frac{.216}{\sqrt{r}}\right)\left(2.43 + \frac{1.584}{\sqrt{h}}\right), \quad . \quad (5)$$

where r is the outside radius in inches and h the height in feet.

TABLE V. VALUES OF c.

Diff. of Temp.	c.
2	.57
4	.67
6	.73
8	.78
10	.82
20	.97
40	1.13
60	1.24
80	1.33
100	1.40
150	1.55
200	1.64
300	1.82

It will be noticed that the values of Table IV do not agree with formula (3). This is because these values have already been multiplied by the coefficient c taken from Table V for a difference of temperature of four degrees.

4. Conduction.—The quantity of heat transmitted through the insulation from outer surface

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to inner surface varies directly as the area of the wall, directly as the conductivity of the material, inversely as its thickness, and directly as the difference of temperature between the two surfaces.

The formula for an area of one square foot of a homogeneous wall with plane parallel surfaces is then

$$M = \frac{C(t-t')}{E}, \quad \ldots \ldots \quad (6)$$

in which M = B.T.U. transmitted per hour per one square foot;

C = the conductivity of the wall as given in the following tables;

E = the thickness of the wall in inches;

t = the temperature of the outer wall-surface;

t' = the temperature of the inner wall-surface.

The conductivity, designated by C, is the quantity of heat that would traverse in one hour a plate of the given material one square foot in area, one inch thick, and with its surfaces

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maintained at temperatures differing by one degree.

In Table VI are given the values of C for a large number of materials as determined with great care and skill by Péclet.

TABLE VI. VALUES OF C.

In B T.U. transmitted per hour, per square foot, for one inch of thickness, for one degree difference of surface temperatures.

SOLID MATERIALS.

	Density.	C.
Marble, gray, fine-grained	2.68	28.1
Marble, white, coarse-grained	2.77	22.4
Limestone, fine-grained	2.34	16.8
Limestone, "	2.27	13.6
Limestone, "	2.17	13.7
Limestone, coarse-grained	2.24	10.6
Limestone, "	2.22	10.2
Plaster, ordinary	2.22	2.67
Plaster, " , very fine	1.25	4.20
Brick	1.98	5.56
Brick	1.85	4.11
Fir (wood), perpendicular to fibres	.48	.75
Fir " parallel " "	.48	1.37
Walnut, perpendicular " "	.48	.86
Walnut, parallel " "	....	1.40
Oak, perpendicular " "	....	1.70
Cork	.22	1.15
India-rubber	.22	1.37
Gutta-percha	.22	1.39
Starch paste	1.02	3.43
Glass	2.44	6.05
Glass	2.55	7.10

(*Continued on next page.*)

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TABLE VI—*Continued.*

MATERIALS IN A STATE OF POWDER.

	Density.	C.
Quartz sand	1.47	2.18
Brick-dust—large grains	1.00	1.12
Brick-dust—passed through a sieve of silk	1.76	1.33
Brick-dust—fine powder obtained by decantation	1.55	1.13
Chalk, in powder, slightly damp	.92	.897
Chalk, in powder, washed and dried	.85	.694
Chalk, in powder, washed, dried, and compressed	1.02	.855
Wood-ashes	.45	.484
Mahogany sawdust	.31	.524
Charcoal, powdered	.49	.637
Charcoal, powdered and passed through silk	.41	.653
Coke, in powder	.77	1.290

TEXTILE MATERIALS.

Canvas, of hemp, new	.54	.420
Canvas, " " old	.58	.347
White writing-paper	.85	.347
Gray blotting-paper	.48	.274
Calico, new, of any density	....	.403
Cotton wool, " " "	....	.323
Sheep's wool, " " "	....	.323
Eiderdown, " " "	....	.315

Table VII was computed from tests of steam-pipe coverings. The figures given are averages of a large number of tests and are believed to be very reliable. *

* See Paulding, "Condensation of Steam in Covered and Bare Pipes." Van Nostrand, 1904.

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TABLE VII. VALUES OF *C*.

Hair-felt	.32
Remanit	.36
Mineral wool (*a*)	.38
" " (*b*)	.40
" " (*c*)	.47
Compressed sheet cork	.47
Magnesia	.45
Asbestos (*a*)	.57
" (*b*)	.61
" (*c*)	.67
" (*d*)	.74

Mineral wools *a* and *b* contained eighteen per cent of magnesia, while *c* had only three per cent of that substance. Asbestos *a* and *d* are made by the same firm, but *a* is much the more expensive covering, probably of selected material. Asbestos *b* and *c* are formed of small air-cells.

Table VIII was computed from the results of experiments given by Mr. J. E. Starr in a paper read before the American Warehousemen's Convention in 1901.*

TABLE VIII. VALUES OF *C*.

Lampblack	.91
Pitch	.74
"	.95
American spruce	.93
" "	.94
Mineral wool	.69
" "	.82
Granulated cork	.48
Calcined pumice	.61
Mill-shavings	.65

* See "Ice and Refrigeration," Nov. 1901.

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Table IX is from Jude and Gossin—"Physics," 1899.

TABLE IX. VALUES OF *C*.

Silver	4440
Copper	3192
Gold	2100
Zinc	888
Tin	572
Iron	476
Lead	334
Ice	17.42
Snow	2.03
Water	4.41
Air	0.16

Péclet states that dampness greatly increases the conductivity of insulating materials, a fact now well known to all refrigerating engineers. One of the most important problems in the construction of insulated walls is to prevent the entrance of moisture.

5. Formula for a Homogeneous Wall.—Let figure 1 represent, as before, a wall of the same material throughout its thickness. Let T and t be the temperatures of the outer air and the outer wall-surface respectively, and T' and t' the temperatures of the inner air and the inner wall-surface. Let M be the B.T.U. transmitted through one square foot of the wall in one hour: this is, of course, the quantity we wish to deter-

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mine. Then from paragraphs 2 and 3 we know that

$$M=(K+K')(T-t)=Q(T-t) \quad . \quad . \quad (7)$$

and $$M=(K+K')(t'-T')=Q(t'-T'), \quad . \quad (8)$$

and from paragraph 4 we have

$$M=\frac{C(t-t')}{E} \quad . \quad . \quad . \quad . \quad . \quad (9)$$

Now in practice we never know the temperatures t and t' of the wall-surfaces, but since the three equations above are all equal to one another (see paragraph 1) we can by combining them obtain the following formula in terms of the inner and outer air temperatures, which we may always easily measure.

$$M=\frac{CQ(T-T')}{2C+QE}, \quad . \quad . \quad . \quad . \quad (10)$$

in which M = B.T.U. transmitted per hour per one square foot;

C = the conductivity of the material (par. 4);

$Q=K+K'$ (pars. 2 and 3);

E = the thickness of the wall in inches;

T = the temperature of the outer air;

T' = the temperature of the inner air.

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For example take a wall of brick sixteen inches thick and thirty-two feet high. Let the temperature of the outer air be sixty degrees and that of the inner air forty degrees. From Table I, par. 2, we find that $K = .74$; from Table IV, par. 3, we find that $K' = .27$, then $Q = .74 + .27 = 1.01$, and from Table VI, par. 4, we find the value of C to be about 5. Then each square foot of this brick wall under the given temperature conditions will transmit

$$M = \frac{5 \times 1.01 (60 - 40)}{2 \times 5 + 1.01 \times 16} = 3.87 \text{ B.T.U.}$$

per hour.

Returning now to formula (10) we must note that in order to have such a simple formula it has been necessary to make some assumptions which are not strictly true. Their effect on the results are however comparatively small. In equations 7 and 8 we have set the sums of $K + K'$ for both outer and inner wall-surfaces equal to Q, which is of course to assume them equal. In finding Q it is perhaps best to take for K and K' averages of the values appropriate to the inner and outer walls, where, as generally happens, these values are different. In formula (7) we assume that the objects which radiate heat to the walls are at the

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same temperature as the outer air. This assumption is unavoidable and under practical conditions the error is probably more or less compensatory, the transmission being greater on a clear day and less on a clear night. In formula (8) we assume that the objects to which the inner wall-surfaces radiate are at the temperature of the inner air, and this is practically true except when the wall radiates directly to cold pipe surfaces, and this is negligible unless the proportion of surface thus exposed is unusually large. In such unusual cases an allowance may be made in the value of Q. In comparing the insulating values of different walls, one of the most important uses of these formulas, these errors either do not exist or else have so nearly the same value for all the cases as not to influence the comparative results.

It is evident from an inspection of the formula that the transmission of heat varies directly as the difference of the inner and outer air temperatures, but not quite inversely as the thickness of the wall. Thus if the wall had been eight inches thick the value of M would have been 5.59, and not twice 3.87 or 7.74, as might have been thought.

6. Formula for a Compound Wall.—Take first a wall of two different materials as represented

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by figure 2. Let C and C' be the conductivities and E and E' the thicknesses of the two materials,

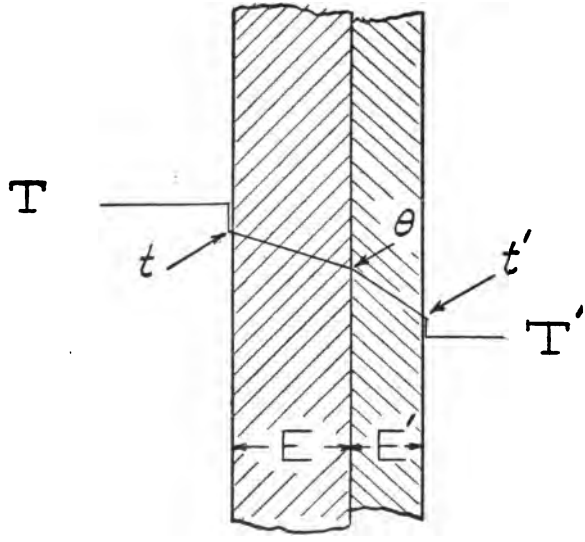

FIGURE 2.

and let θ represent the temperature at the junction of the materials. Then as in paragraph 5 we may write the following equations:

$$M = Q(T - t), \qquad M = Q(t' - T'),$$

$$M = \frac{C(t - \theta)}{E}, \qquad M = \frac{C'(\theta - t')}{E'}.$$

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Combining these we have

$$M = \frac{Q(T - T')}{2 + Q\left(\frac{E}{C} + \frac{E'}{C'}\right)} \quad . \quad . \quad . \quad . \quad (11)$$

For a wall made up of any number of layers of different materials we would have

$$M = \frac{Q(T - T')}{2 + Q\left(\frac{E}{C} + \frac{E'}{C'} + \frac{E''}{C''} + \ldots\right)}, \quad . \quad (12)$$

in which M = B.T.U. transmitted per hour per one square foot;

C, C', C'' = the respective conductivities of the different layers (par. 4);

$Q = K + K'$ (pars. 2 and 3);

E, E', E'' = the respective thicknesses in inches of the different layers;

T = the temperature of the outer air;

T' = the temperature of the inner air.

For an example take the wall shown in figure 3. This consists of an outer layer of seven-eighth-inch tongued and grooved spruce sheathing (conductivity from Table VIII equals .93), then a layer of water-proof paper about. 03 inch thick

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(conductivity by Table VI equals .27), then 1½ inches of hair-felt (conductivity by Table VII

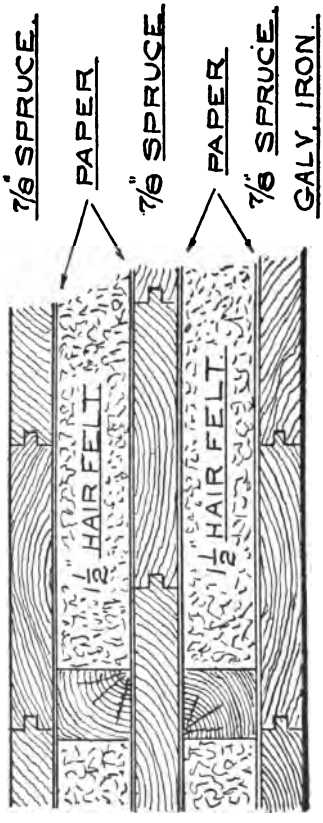

FIGURE 3.

equals .32), then paper, spruce, paper, hair-felt, paper, spruce, and galvanized iron.

On account of the ease with which it transmits

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heat, we may pay no attention to the galvanized iron except to choose a value of K midway between that due to the iron (.57) and that due to the outer painted surface (.76).

Let us suppose the height of the wall to be 10 feet. Then $Q = .30 + \frac{1}{2}(.57 + .76) = .97$.

Let the temperature of the outer air be ninety degrees and that of the inner twenty degrees. Then by formula (12) we have

$$M = \frac{.97(90 - 20)}{2 + .97\left[3\left(\frac{.875}{.93}\right) + 4\left(\frac{.03}{.27}\right) + 2\left(\frac{1.5}{.32}\right)\right]} = 4.78.$$

7. Formula for a Wall Containing an Air-space.— Let figure 4 represent two walls built with an air-space, closed at top and bottom, between them. Let x and x' be the temperatures of the two sides of the air-space, then the heat will be carried across by radiation and by air contact, and we may say without much error that

$$M = (K + K')(x - x') = Q(x - x').$$

Now if the air-space were filled with insulating material of thickness E and conductivity C, the transmission would be equal to $\frac{C}{E}(x - x')$. Then

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in the general formula we may substitute $\frac{1}{Q}$ for $\frac{E}{C}$ and we have, for one air-space,

$$M = \frac{Q(T - T')}{2 + Q\left(\frac{E}{C} + \frac{1}{Q} + \frac{E'}{C'}\right)}, \quad . \quad . \quad (13)$$

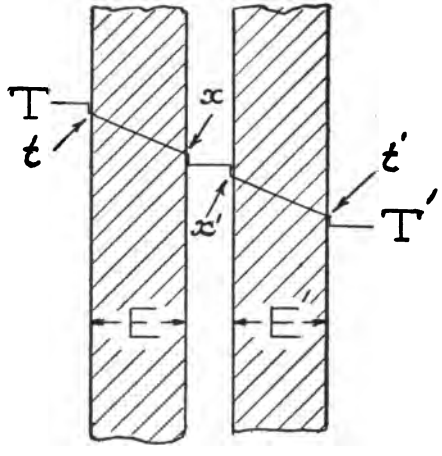

FIGURE 4

and for any number of air-spaces

$$M = \frac{Q(T - T')}{2 + Q\left(\frac{E}{C} + \frac{1}{Q} + \frac{E'}{C'} + \frac{1}{Q} + \frac{E''}{C''} + \ldots\right)}. \quad (14)$$

For the notation see equation (12) of the previous paragraph.

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As a numerical example let figure 4 represent a double brick wall 32 feet high, with an air-space, and let each half of the wall be 8 inches thick. Let the temperature of the outer air be sixty degrees and that of the inner forty degrees. Then, referring to the numerical example given in paragraph 5, a solid brick wall 16 inches thick, we have $C=5$ and $Q=1.01$. Then, by formula (13),

$$M=\frac{1.01(60-40)}{2+1.01\left(\frac{8}{5}+\frac{1}{1.01}+\frac{8}{5}\right)}=3.24.$$

Now the 16-inch solid wall transmitted 3.87 B.T.U. per hour per square foot; we have then decreased the transmission about sixteen per cent by adding the air-space.

For a second example we may turn to figure 3 and suppose the hair-felt removed, leaving two air-spaces, but all other conditions of the example in paragraph 6 remaining unchanged. In the formula, then, we drop out the term representing the hair-felt and substitute the value of $\frac{1}{Q}$, which

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in this case would be $\frac{1}{.30+.76}=\frac{1}{1.06}$; we have then

$$M=\frac{.97(90-20)}{2+.97\left[3\left(\frac{.875}{.93}\right)+4\left(\frac{.03}{.27}\right)+2\left(\frac{1}{1.06}\right)\right]}=9.70.$$

We have, in this case, practically doubled the transmission by substituting air-spaces for hair-felt.

These two examples show how we may determine the value of an air-space in any given case, but a general view of the subject may be useful.

Returning to the formula, equation (13), or, better, to the reasoning preceding it, we see that the thickness of the air-space is of no effect. Experiments have repeatedly shown this to be true, or approximately so, for ordinary thicknesses. Taking one inch as a practical thickness for ordinary construction, and the value of $\frac{1}{Q}$, lying very near to unity, for a material to be of the same value as the air-space, $\frac{C}{E}$ must equal unity, and for the same thickness, namely one inch, C must equal unity. This is about true for ordinary

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spruce; for almost any of the other materials used in insulation the air-space would be a disadvantage in a wall of fixed thickness. Of course an added air-space that does not displace any insulating material is always a help, but space is frequently too valuable for this construction to be used.

8. Floors and Ceilings.—The formulas of the preceding paragraph are in strictness only applicable to vertical walls; but they are equally applicable to floors and ceilings in every respect except the air-contact action, represented in the formulas by the coefficient K', for the conductivity and the radiation are of course unaffected by the position of the wall. In practical cases, on account of the considerable thickness of the insulation we may use the same value of K' as for the side walls without fear of much error, for, though the air-contact action will be low for the ceiling, it should be high for the floor, and the average cannot be far enough from the usual value of K' to seriously affect the result.

9. Experimental Proof of the Formulas. — Reliable experiments on the transmission of heat through insulation, under conditions representing actual practice, are very rare, but the following

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tests, made some years ago by the Nonpareil Cork Manufacturing Co., are believed to be unusually good.

The apparatus consisted of an insulated box, $6' \times 3' \times 3'$ inside measurement, containing an electric heating-coil, the whole placed in a room $12' \times 10' \times 8'$ maintained at a constant temperature by air cooled by an ice-machine. One side of the insulated box was removable, and sides built up of any desired insulation could be substituted for it. The area exposed was taken as the mean of the exterior and interior surfaces. The figures hereinafter given for the transmission in each case are per degree difference of inner and outer air temperatures and are taken from blue-prints issued by the cork company about 1899. In another circular they state that the inner and outer temperatures were held at one hundred degrees and ten degrees respectively; this does not, however, enter into our calculations.

The insulations tested were all combinations of spruce sheathing and compressed sheet cork; they are shown in detail in the following figures. The value of the conductivity of spruce we take from Table VIII as .93; that of water-proof paper .27, as indicated by Table VI; and that of com-

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pressed sheet cork as .50, as indicated by the experiments themselves. The value of K we

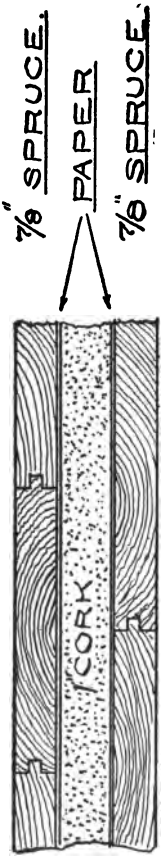

FIGURE 5.

find from Table I to be .74; and from Table IV K' is .33, and therefore Q equals 1.07.

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Experiment I.

INSULATION AS SHOWN IN FIGURE 5.

Heat transmitted, in B.T.U. per hour, per square foot, per degree difference of temperature: by the experiment = .175.

By formula (12),

$$M = \frac{1.07 \times 1}{2 + 1.07\left(2 \times \frac{.875}{.93} + 2 \times \frac{.03}{.27} + \frac{1}{.50}\right)} = .168$$

Experiment II.

Insulation as in Exp. I., except two inches of cork instead of one inch.

Heat transmitted: by experiment = .135.

By formula (12),

$$M = \frac{1.07 \times 1}{2 + 1.07(4.10 + 2)} = .126$$

Experiment III.

Insulation as in Exp. II. except three inches of cork instead of two.

Heat transmitted: by experiment = .094.

By formula (12),

$$M = \frac{1.07 \times 1}{2 + 1.07(6.10 + 2)} = .100$$

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Experiment IV.

INSULATION AS SHOWN IN FIGURE 6.

Heat transmitted: by experiment =.125.

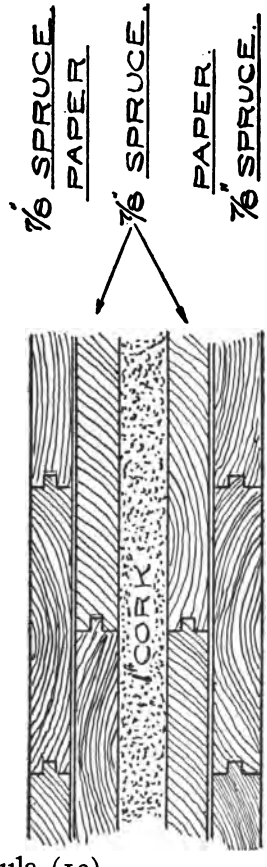

FIGURE 6.

By formula (12),

$$M = \frac{1.07 \times 1}{2 + 1.07(4 \times .94 + 2 \times .11 + 2)} = .128$$

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Experiment V.

INSULATION AS SHOWN IN FIGURE 7.

For the air-space, $\frac{I}{Q} = .93$.

⅞" SPRUCE
PAPER.
1" CORK.
1" AIR SPACE
1" CORK
PAPER.
⅞" SPRUCE.

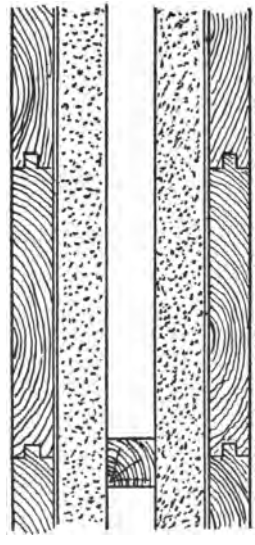

FIGURE 7.

Heat transmitted: by experiment = .117

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By formula (13),

$$M = \frac{1.07 \times 1}{2 + 1.07(2 \times .94 + 2 \times .11 + 2 \times 2 + .93)} = .112$$

EXPERIMENT VI.

Insulation as in figure 7, except that a layer of one-inch cork is replaced by one of seven-eighths spruce sheathing.

Heat transmitted: by experiment = .146

By formula (13),

$$M = \frac{1 \times 1.07}{2 + 1.07(3 \times .94 + 2 \times .11 + 2 + .93)} = .128$$

To those who are familiar with the difficulties of tests of this kind the agreement between theory and tests will probably be not unsatisfactory, except in the case of the last experiment. It will be noticed that the insulation in this experiment is the same as in the previous one except that a layer of spruce sheathing has been substituted for a layer of cork. To get the result given in the test we should have to assume the spruce to be of no value whatever, which is obviously absurd.

Some steam-pipe coverings of compressed cork were included in some very extensive tests made a few years ago by Mr. Geo. H. Barrus, and I have

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computed the value of the conductivity in that case to have been .47. This agrees fairly with the value .50 found to suit best the tests just described.

10. Insulation of Brine-pipes. — In the case of a covered pipe conveying cold brine or ammonia-gas, there are four stages in the process of the absorption of heat:

1st. The passage of the heat from the air into the surface of the covering, by radiation from the surrounding objects and the air-contact action of the surrounding air.

2d. The conduction of the heat through the covering from its outer to its inner surface.

3d. The conduction of the heat through the metal of the pipe

4th. The escape of the heat from the inner surface of the pipe to the liquid or gas traversing the pipe.

On account of the high conductivity of the metal of the pipe, the ease with which heat escapes from a surface to a *rapidly moving* liquid, or even gas, bathing that surface, and the small quantity of heat permitted to pass by the insulating covering, we may entirely neglect the third and fourth stages of the process. This is

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equivalent to saying that the temperature of the inner surface of the covering is the same as that of the brine or gas circulating through the pipe.

The first and second stages depend on exactly the same principles as in the case of the walls of a refrigerated room, and from these laws we get the following formula:

$$U = \frac{2\pi R'Q(T-t')}{1 + \frac{12NR'Q}{C}}, \quad . \quad . \quad . \quad (15)^*$$

* If we consider an infinitely thin annular element of the covering, one foot long, at radius r, its thickness is dr, its area $2\pi r$, its conductivity per one foot thickness is C', equal to $\frac{C}{12}$, and the difference between the temperature of its inner and outer surfaces is dt. Then, treating it as a flat plate, we have by paragraph 4

$$U = \frac{2\pi r C' dt}{dr}, \quad \text{or} \quad C' \int_{t'}^{t} dt = \frac{U}{2\pi} \int_{R}^{R'} \frac{dr}{r},$$

where t = temperature of the outer surface of the covering. Integrating, and changing from hyperbolic to common logarithms, we get

$$U = \frac{2\pi C'(t-t')}{2.3(\log R' - \log R)} = \frac{2\pi C'(t-t')}{N}.$$

We know from the principles of paragraphs 2 and 3 that

$$U = 2\pi R'Q(T-t).$$

By combining these last two equations and writing $\frac{C}{12}$ for C' we get

$$U = \frac{2\pi R'Q(T-t')}{1 + \frac{12NR'Q}{C}}. \quad . \quad . \quad . \quad . \quad . \quad (15)$$

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in which U = the B.T.U. per hour *per foot run* absorbed through the covering;

$\pi = 3.1416$;

R' = radius in feet of the outer surface of the covering (see Table X);

$N = 2.3$ (logarithm of R' − logarithm of R) where R is the radius in feet of the outer surface of the pipe (see Table X);

$Q = K + K'$, in which K is the radiation coefficient appropriate to the material forming the surface of the covering, and is to be taken from Table I; while K' is the air-contact coefficient to be taken from Table X or from formula 4 or 5 of paragraph 3;

C = the conductivity of the material of the covering taken from the tables of paragraph 4;

T = the temperature of the air surrounding the covered pipe;

t' = the temperature of the brine or gas circulating through the pipe.

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TABLE X.—FOR USE WITH FORMULA (15).

Nominal Pipe Size.	Thickness of Covering in Inches.	Radius in Feet. R'.	Square Feet per Foot Run. $2\pi R'$.	$12R'N$.	For Horizontal Pipe. K'.
1″	0	.055	.356	.....	.89
	½	.097	.609	.660	.68
	1	.138	.870	1.530	.61
	1½	.180	1.130	2.560	.56
	2	.221	1.389	3.688	.54
	2½	.263	1.652	4.928	.52
	3	.305	1.915	6.260	.50
1½″	0	.078	.491	.....	.75
	½	.121	.759	.639	.63
	1	.163	1.022	1.425	.58
	1½	.204	1.283	2.350	.55
	2	.246	1.546	3.390	.52
	2½	.288	1.810	4.505	.51
	3	.329	2.069	5.665	.50
2″	0	.099	.62	.....	.68
	½	.141	.89	.593	.60
	1	.183	1.15	1.335	.56
	1½	.224	1.41	2.190	.54
	2	.266	1.67	3.145	.52
	2½	.308	1.94	4.192	.50
	3	.349	2.19	5.273	.49
2½″	0	.120	.75	.....	.63
	½	.162	1.02	.579	.58
	1	.204	1.28	1.290	.55
	1½	.245	1.54	2.093	.52
	2	.287	1.80	2.997	.51
	2½	.328	2.06	3.952	.50
	3	.370	2.32	4.999	.49
3″	0	.146	.92	.....	.60
	½	.188	1.18	.565	.56
	1	.229	1.44	1.240	.53
	1½	.271	1.70	2.010	.51
	2	.313	1.96	2.857	.50
	2½	.354	2.22	3.754	.49
	3	.396	2.49	4.730	.49

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TABLE X—*Continued.*

Nominal Pipe Size.	Thickness of Covering in Inches.	Radius in Feet. R'.	Square Feet per Foot Run. $2\pi R'$.	$12\,R'N$.	For Horizontal Pipe. K'.
4″	0	.188	1.18	.....	.56
	½	.229	1.44	.553	.53
	1	.271	1.70	1.196	.51
	1½	.313	1.96	1.915	.50
	2	.354	2.22	2.682	.49
	2½	.396	2.49	3.533	.49
	3	.438	2.75	4.434	.48
5″	0	.232	1.46	.....	.53
	½	.273	1.72	.541	.51
	1	.315	1.98	1.160	.50
	1½	.357	2.24	1.847	.49
	2	.398	2.50	2.574	.49
	2½	.440	2.77	3.371	.48
	3	.482	3.03	4.220	.48
6″	0	.276	1.73	.....	.51
	½	.318	2.00	.534	.50
	1	.359	2.26	1.133	.49
	1½	.401	2.52	1.795	.49
	2	.443	2.78	2.512	.48
	2½	.484	3.04	3.259	.48
	3	.526	3.30	4.063	.47
8″	0	.359	2.26	.....	.49
	½	.401	2.52	.529	.49
	1	.443	2.78	1.110	.48
	1½	.484	3.04	1.738	.48
	2	.526	3.30	2.410	.47
	2½	.568	3.57	3.120	.47
	3	.609	3.83	3.859	.46

For a numerical example we will take a 1½-inch standard pipe, running horizontally, covered with an insulation two inches thick and of conductivity .64. Let the temperature of the sur-

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rounding air be eighty degrees and the brine within the pipe be at a temperature of twenty degrees. What will be the absorption of heat per hour per foot run in B.T.U.?

In this example we may take the quantities $2\pi R'$, $12NR'$, and K' directly from Table X; their values are 1.55, 3.39, and .52 respectively. If we suppose the outer surface of the covering coated with paint we may take $K=.76$, then $Q=.52+.76=1.28$ and our formula becomes

$$U=\frac{1.55\times 1.28(80-20)}{1+\frac{3.39\times 1.28}{.64}}=15.30.$$

If the brine in this pipe were to travel at a speed of 150 feet per minute, there would pass in one hour 8940 pounds of a specific gravity of 1.12 and a specific heat of .86. To raise the temperature of this one degree would require $8940\times.86=7688$ B.T.U. If we divide this figure by 15.30 we get the length of pipe through which the brine may be carried before its temperature rises one degree. This works out at about 500 feet.

Returning to formula (15) we see at once that the amount of heat absorbed varies directly as the

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difference of temperatures of the surrounding air and the brine. In regard to the variation due to the conductivity, C, of the covering, we see from the formula that although the absorption does not vary directly with this, still the departure from this law is not great. Thus in our numerical example, if we had employed hair-felt with a conductivity of .32 instead of the material with C equal to .64 we should have found U to equal 8.17, which is not so far from half of 15.30. But in regard to the variation of the absorption as the thickness of the covering is changed the law is complicated. If we consider a covering composed of two cylindrical layers of equal thickness, it is evident that while the resistance due to thickness will be the same in both, the outer layer will present a greater area for the passage of the incoming heat and therefore will be less effective than the inner layer. Moreover, the addition of the outer layer has increased the superficial area per foot run, thus giving a greater opportunity for air contact and radiation. The greater the diameter of the pipe the nearer does each layer come to being equally effective. Returning to our numerical example the variation of absorption with thickness would be as follows:

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1½-inch Pipe, Horizontal. Thickness of Covering. ($C = .64$)	Brine, 20°; Air, 80°. B.T.U. per Hour per Foot Run. (Diff. of Temp. = 60°)
½″	26.55
1 ″	20.58
1½″	17.35
2 ″	15.30

By the principles laid down in paragraphs 2 and 3 the absorption of heat by a bare pipe under the conditions of our numerical example can be readily obtained.

The formula is:

$$U = 2\pi R' Q(T - t'), \quad . \quad . \quad . \quad (16)$$

and from Table X, $2\pi R'$ is .491, while K' is .75. From Table I, K is about .57, therefore $Q = .75 + .57 = 1.32$ and $U = .491 \times 1.32 \times 60 = 38.89$.

This figure shows that the two-inch covering has reduced the loss to $15.30 \div 38.89 = 39.4$ per cent of that which occurs with a bare pipe. If the covering had been of hair-felt, which represents about the highest commercially obtainable efficiency, the loss would be only $8.17 \div 38.89 = 21$ per cent. Of course a bare pipe would soon coat itself with snow and thus decrease the absorption, but for purposes of comparison we cannot consider this.

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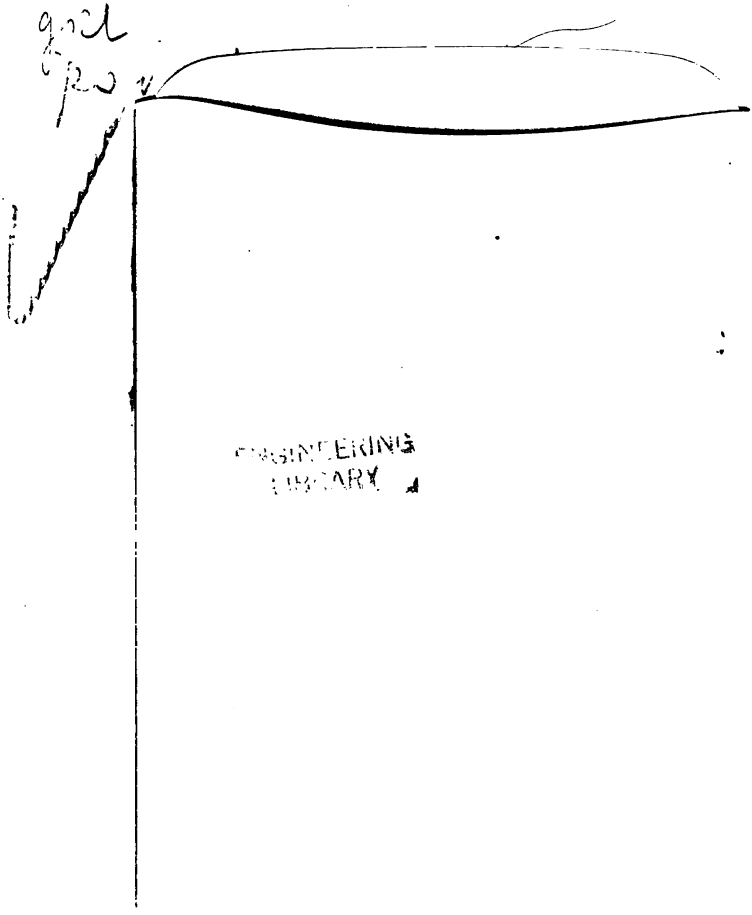

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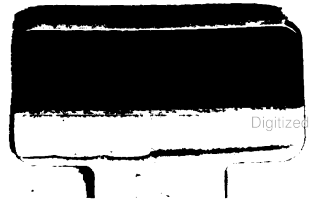

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